Review of GB Electricity Distribution System's Electricity Security of Supply, Reliability and Power Quality in Meeting UK Industrial Strategy Requirements

Citation for published version:
Vegunta, SC, Watts, CFA, Milanovic, JV, Djokic, S & Higginson, M 2019, 'Review of GB Electricity Distribution System's Electricity Security of Supply, Reliability and Power Quality in Meeting UK Industrial Strategy Requirements', *IET Generation, Transmission and Distribution*. https://doi.org/10.1049/iet-gtd.2019.0052

Digital Object Identifier (DOI):
10.1049/iet-gtd.2019.0052

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
IET Generation, Transmission and Distribution

Review of GB Electricity Distribution System's Electricity Security of Supply, Reliability and Power Quality in Meeting UK Industrial Strategy Requirements

Sarat Chandra Vegunta[1*], Christopher François Anthony Watts[2], Jovica V. Milanović[3], Sasa Z. Djokic[4], Michael J. Higginson[1]

[1] Consulting & Analytical Services, S&C Electric Company, 6601 N Ridge Blvd, Chicago, IL 60660, USA
[2] Regulatory Affairs, S&C Electric UK Holdings Ltd., Brunel Way, Baglan Energy Park, Neath SA11 2FP, UK
[3] School of Electrical and Electronic Engineering, The University of Manchester, Manchester M1 3BB, UK
[4] School of Engineering, The University of Edinburgh, Edinburgh EH9 3FB, UK
[*]Sarat.Vegunta@sandc.com

Abstract: The United Kingdom (UK) Government's 2017 Industrial Strategy outlines a bold plan centred on making the UK one of the most competitive places in the world to start or grow a business, building on the UK's strengths, extending excellence into the future, and closing the gap between the UK's best performing companies, industries, places and people, and those viewed as less productive. In the context of delivering this strategy, from power system reliability and power quality points of view, this paper explores the various challenges and gaps in the Great Britain (GB) electricity distribution system, which is recognised as among the most complex forms of energy exchange that will become the backbone of the emerging digital economy and Industry 4.0. Additionally, the paper also provides recommendations to address the identified challenges.

1. Introduction

The UK Government's 2017 Industrial Strategy Green Paper [1] recognises that there are various challenges the UK must face, both now and in the years ahead. These include, but are not limited to, the following: building on the UK's strengths and extending excellence into the future; closing the gap between the UK's best-performing companies, industries, places and people, and those recognised as less productive; and making the UK one of the most competitive places in the world to start or grow a business. The Green Paper also recognises that: the UK has often been slower than competitors when it comes to taking up and deploying existing technologies (for example: the UK makes less use of robotics and automation than most other countries in Western Europe); the UK's overall infrastructure is perceived by international businesses as worse than its competitors; and there is a need to upgrade energy, transport, water, flood defence and digital infrastructure across the country. In mind of such considerations, the UK Government outlined an objective in 2017 centred on improving living standards and economic growth by increasing productivity across the whole country [1] .

In 2015, approximately two-thirds of the UK's Gross Value Added (GVA) was related to non-financial businesses, which was composed of an estimated 56% of non-financial services, 19% production (of which manufacturing accounted for 74%), 17% distribution, 8% construction and 0.2% agriculture sectors, respectively [2]. Although the current share of electricity as a primary fuel is less than 50% among non-domestic sectors (i.e. service, industry and transport) and the domestic sector [3], the share of electricity use in these sectors, as based on future green ambition projections, will rise significantly [4]. A notable increase in the penetration of Electric Vehicles (EVs) and decarbonisation of heat are needed in order to meet the UK's overall decarbonisation targets, as described in the green ambition projections [4]. This means that the share of electrical energy consumption by end-use, which is currently dominated by non-heat and non-transport loads [3], will change with anticipated electrification of road transportation and heating, but also as a result of the growth in urbanisation, automation, robotics and sensors, etc. [4, 5].

The combination of generation technologies and parts of the network to which they are connected is also experiencing a rapid shift. For example, the UK National Grid's Future Energy Scenarios publication [4] predicts that the total amount of GB renewable generation capacity could rise from 37% of total installed capacity in 2017 to as much as 63% by 2050, with the total Distributed Generation (DG) capacity able to rise from 27% in 2017 to as much as 65% by 2050. This means that electricity is not only a primary source of fuel for end-use consumption of energy, but also that electricity networks and connected systems are increasingly acting as a platform for energy exchanges and energy conversions, with electricity networks accommodating a much greater spectrum of distributed and transmission connected generation. The need for electricity networks to be planned, built and operated in such a way that ensures the energy transfer between electricity network and connected systems is predictable, reliable, high-quality, and efficient—meaning that the customer and UK economic productivity needs (to the extent of electricity fuel's share and electricity supply impact on such productivity) are met—is therefore more important than ever before.

Over the last few decades, due to the privatisation and reform of GB electricity markets, technical innovations and improvements in technology, as well as government initiatives to address climate change, the amount of DG connected to the electricity distribution system has rapidly increased, subsequently affecting systems' characteristics, performance and operation. A sheer volume of load, generation and electricity supply equipment connected to the GB distribution system, together with the increase in the penetration of the low-carbon generation and active-load technologies, such as Photovoltaics (PVs) and EVs, etc., as well as the increase in the number of smart metering, measurement and control devices, have all contributed to the overall distributed system's operational complexity; the burden to provide operational flexibility, while at once accommodating such operational complexity, is therefore even greater. This has led the Energy Networks Association (ENA)—the industry body for Distribution Network Operators (DNOs) in GB—to create the Open Networks Project initiative [6] in order to develop requirements for the transition from a GB DNO to a GB Distribution System Operator (DSO), including consideration of the impact on existing organisational capability.

To the best of the authors' knowledge, *no information is available in the open literature that, from electricity distribution related security of supply, reliability and power quality perspectives, connects the following aspects and provides suggestions for improvements in the GB regulatory policy associated with the electricity distribution*: i) the UK Government's industrial strategy and vision; ii) the current state of the UK's competitiveness globally, particularly from an electricity supply reliability context; iii) the electricity supply requirements of the changing UK manufacturing sector; iv) the current state of distributed energy resources connected to the electricity distribution supply system and reliability performance of that system; v) the contribution of smart meters in allowing improved observability of electricity supply quality and to support electricity reliability and power quality; vi) utility-customer equipment electrical compatibility and interoperability; and vii) principal performance trends and insights in the existing distribution system and related regulatory framework. *Some of these aspects were considered independently in the available literature; however, they have not been analysed together, nor have they considered the overall context of the UK industrial strategy and vision delivery.*

2. Global Competitiveness

The recent World Economic Forum (WEF)'s Global Competitiveness (GC) reports [7, 8] highlight that the Fourth Industrial Revolution, i.e. the Industry 4.0—which is based on digital platforms and characterised by a convergence of technologies that is blurring the lines between the physical, digital and biological spheres—is gathering pace. In addition, it has also been highlighted that economies depend on it, including key infrastructures, such as electricity supply, transport and telecommunications, etc. [7].

Undoubtedly, the electrical devices that will deliver Industry 4.0 and digital economy will be reliant on the power quality performance (notably a step beyond the electricity-reliability-based performance) of the electricity supply, particularly of the distribution system to which they will connect.

The report in [7] also highlights the importance of supporting the emergence of new sectors of economic activity through competitiveness reforms that foster innovation. Nonetheless, as the Global Competitiveness Index (GCI) shows, to date, progress in building an enabling-environment for innovation remains the advantage of only a few economies. The 2018 GCI overall rank for the UK is 8th, with the top three ranks held (in the descending order) by the US, Singapore and Germany [8].

3. Security of Supply, Reliability and Power Quality Definitions

As the GB is an island, and as there is currently a limited capacity of interconnectors with the rest of the continental Europe, the security of supply has a great importance for the GB electricity supply system.

Currently, in the GB electricity supply context, the 2018 Grid Code [9], the 2017 National Electricity Transmission System Security and Quality of Supply Standard (NETS SQSS) [10], and the 2018 Distribution Code [11] do not clearly define nor have standardised definitions for security of supply, quality of supply, and power quality.

The Energy Networks Association (ENA) Engineering Recommendation (EREC) P2/6 Security of Supply document [12] defines *supply security*, or security of supply, as: the capability of a system to maintain supply to a defined level of demand under defined outage conditions. It should, however, also incorporate measures of both physical and cyber security, as they can affect the delivery of electric energy [13]. Although in the GB electricity transmission context and as per the UK Government's definition, a measure of electricity reliability for security of electricity supply is expressed as a Loss of Load Expectation (LOLE) of 3 hours per year [14], the security of supply in the electricity distribution is primarily driven by the requirements in the ENA EREC P2/6, together with the requirements and incentives under the OFGEM RIIO-ED1 [15] price control arrangements in place for electricity distribution.

The quality of supply—a synonymous term to electricity supply reliability, as defined in [13]—relates to the measure of number, duration, and severity of the electricity supply outage events.

The IEC 61000-4-11 Std [16] provides specific definitions for a voltage dip or sag and a short interruption [17]. In GB, Customer Interruptions (CI, per year) and the Customer Minutes Lost (CML, per customer per year) are the two main reliability performance indicators used to quantify quality of supply [18]. (Note: There's also a Customers Re-interrupted (RIs) metric in GB [18]. Although this metric is not included in the CI metric and related incentives, the CMLs associated with the RIs are, however, included in the CMLs and related incentives.) These CI/CML definitions are analogous to, but not the same as, the IEEE 1159-2009 Std [19] based sustained interruption and related duration definitions, which are part of a broad voltage event magnitude-duration-based classification (see Fig. 1). For example, in GB, a supply interruption of less than three minutes is recognised as a 'short interruption' (the IEEE 1159-2009 Std. duration limit for a 'short interruption', based on a 'temporary interruption' definition per Fig. 1, is one minute) and a supply interruption longer than three minutes is considered an 'interruption' or 'customer interruption' (the IEEE 1159-2009 Std duration limit for an 'interruption', based on a 'long interruption' definition per Fig. 1, is greater than a minute), both of which in GB are currently included as part of GB's system reliability performance. A similar duration-based separation is applied to distinguish voltage sags from under-voltages.

Categories	Typical Dur.	Typical Vol. Mag.
1 Transients	50 ns – 1 ms	-
2 Short duration RMS variations		
2.1 Instantaneous	0.5-30 cycles	0.1-0.9 p.u.
2.1.1 Sag	0.5-30 cycles	1.1-1.8 p.u.
2.1.2 Swell		
2.2 Momentary	0.5 cycles – 3 s	<0.1 p.u.
2.2.1 Interruption	30 cycles – 3 s	0.1-0.9 p.u.
2.2.2 Sag	30 cycles – 3 s	1.1-1.4 p.u.
2.2.3 Swell		
2.3 Temporary	>3 s – 1 minute	<0.1 p.u.
2.3.1 Interruption	>3 s – 1 minute	0.1-0.9 p.u.
2.3.2 Sag	>3 s – 1 minute	1.1-1.2 p.u.
2.3.3 Swell		
3 Long duration RMS variations		
3.1 Interruption, sustained	>1 minute	0.0 p.u.
3.2 Undervotlages	>1 minute	0.8-0.9 p.u.
3.3 Overvoltages	>1 minute	1.1-1.2 p.u.
4 Imbalance		
4.1 Voltage	Steady state	0.5-2.0%
4.2 Current	Steadv state	1.0-30.0%
5 Waveform distortion		
5.1 DC offset	Steady state	0.0-0.1%
5.2 Harmonics	Steady state	0.0-20.0%
5.3 Inter-harmonics	Steady state	0.0-2.0%
5.4 Notching	Steady state	-
5.5 Noise	Steady state	0.0-1.0%
6 Volt. fluctuations	Intermittent	0.1-7.0%
7 Power frequency variations	<10 s	± 0.1 Hz

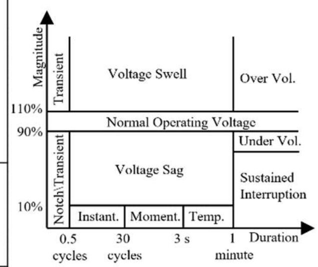


Fig. 1. IEEE 1159-2009 Std. power quality categories and typical characteristics of power system electromagnetic phenomena [19].

Based on [13], power quality relates to the measure of, primarily, voltage quality, including voltage sags (in terms of magnitude and duration), acceptable waveform distortion, flicker, and unbalance levels during both steady state operating conditions and various short-term disturbance events. Currently, *there are requirements (but no regulatory incentives) for reporting short interruptions (but not reporting of their respective durations, or of other power quality metrics) by the GB electricity utilities to OFGEM as part of the current RIIO-ED1 price control* [15]. Among the power quality metrics, voltage sags, short interruptions, and their respective durations are of particular interest and focus here owing to their impact on sensitive electrical equipment, e.g., electrical devices that are expected to deliver Industry 4.0 and digital economy.

4. The UK Manufacturing-Based Electrical Load

A 2016 survey [5] of the UK manufacturing businesses showed that approximately 85% of respondents are either already implementing, or have plans to implement, the Industry 4.0 in the near future. The UK manufacturing, which represents an estimated 10% of the UK's GVA, accounts for about 45% of the UK exports, and which ranks 9th in the world [20], is predominantly connected to the electricity distribution system via non-domestic, half hourly or non-half hourly metered connections.

The survey from [5] also provided further details on a number of aspects, including the type of connectivity technologies currently used in the UK factories, the anticipated level of investment by businesses in these connectivity technologies, and the anticipated level of returns from the related investments. In regards the type of connectivity technologies, the survey concluded that the most widespread application for factory connectivity was Human Machine Interfacing (HMI) devices, which were utilised by 68% of respondents; notably, almost as many respondents (64%) were also taking the next step in connectivity–connecting sensors. Moreover, approximately 68% of those HMIs currently connect to alarms to respond more quickly to out-of-nominal conditions. In addition, more than half (52%) of the respondents also reported connectivity to Programmable Logic Controllers (PLCs), with 32% reporting connectivity to motors and actuators, and about 28% reporting connectivity to robots.

Furthermore, increased production/output, improved quality and accuracy, reduced overall cost of production, reduced production cycle time, and flexibility of production were identified in the survey [5] as the top expected benefits to be garnered from the deployed factory connectivity technologies and related investments made in the UK factories. Although a number of issues, such as lack of expertise and cyber security aspects of factory connectivity technologies, were found to be among the respondents' top list of concerns, around 34% of respondents also expressed concerns with the payback period (on investments made in factory connectivity technologies) and related uncertainty [5]. Such connectivity technologies, which interface directly or indirectly with local electricity distribution systems, are sensitive to the voltage disturbances and fluctuations in the electrical supply, affecting the overall output production and quality of products made in the UK factories, increasing manufacturing costs and uncertainty for the investors.

'Digital economy' devices feature increased interconnectivity and are employed in more complex production processes; these devices and production processes in which they are employed are more sensitive to disturbances, resulting in higher incurred losses due to these disturbances.

4.1. The Impact of Electricity Supply Disturbances on Factory Manufacturing Electrical Equipment

Voltage disturbance tolerances of factory equipment, which are commonly used, or which may become common forms of end-use (e.g., in Industry 4.0), can be seen summarised in Table 1. It is clear from the data in Table 1 that a balanced three-phase voltage sag with a 50% magnitude of nominal voltage lasting for 500 ms at the terminals of a sensitive equipment customer facilities will cause major equipment trip/malfunction and likely cause disruption of the production process (partly, or as a whole). The impact of a short interruption of the same duration will be even more serious, or equally serious, but more certain.

Accordingly, it can be concluded that the likely impact of voltage sags and short interruptions on an increasing share of electronic and power-electronic-based electrical equipment—if no action is taken by OFGEM or GB DNOs—will be greater. For example, according to [21], plug-in EV voltage-sag response, when synchronised across large numbers of plug-in EVs, could result in the loss of a significant proportion of the total load, which could result in unacceptably high voltages once the initiating voltage sag event is cleared. Similar voltage-sag-, swell- or interruption-events could lead to a trip/malfunction of a combination of varied levels of load-generation that could further trigger a voltage/frequency stability event.

Table 1. *Typical factory electrical load equipment's voltage-sag-magnitude-duration uncertainty ranges.*

Factory Equipment	Voltage Sag Tolerance Uncertainty Ranges		Ref.
	Magnitude (p.u.)	Duration (ms)	
AC-Coil Motor Contactors	0.30–0.75	10–80	[22]
Adjustable Speed Drives	0.60–0.85	10–170	[23]
Personal Computers	0.20–0.70	20–380	[24]
Electrical Vehicles	0.80	200	[21]
Programmable Logic Controllers	0.46–0.78	20–2,820	[25]
Factory Automation Robots	0.00–0.5	50–150	[26]

An investigation [27] into a GB pharmaceutical manufacturing plant, which was connected to a 33 kV distribution system and which experienced voltage disturbances (recorded between January 2004 and January 2007) that had caused plant shutdowns, showed that the cost per plant shutdown might be up as much as hundreds of thousands of British pounds.

Furthermore, a power quality survey [28] conducted across 16 industry sectors EU-25 from 68 industry respondents (including 5 in the UK) found that the overall cost of poor power quality-related losses exceeded €150 billion, with 'industry' accounting for more than 90%. The same survey also identified that voltage sags and short interruptions were responsible for around 50% of losses and mostly affected the electronic equipment used in the industry and service sectors. A power quality application guide in [29], as published in 2000, highlights that the UK cost to customers as a result of power quality disturbances amounted to £200 million, which was paid out by insurers for such losses in 1994. The document further suggested that the cost will likely be much higher, up to 50% higher, owing to transients and interruptions as opposed to harmonics. However, the scope of the survey quantifying the financial losses was not clear from the application guide (in [29]) and no information was provided with regards to how wide the survey coverage was in terms of the types of industries surveyed and the impact as a result of different power quality issues. Furthermore, no information was provided with regards to the way in which the financial losses as a result of power quality disturbances were quantified.

Based on survey results in [28], the three-minute threshold time that triggers the count of GB CIs and CMLs, voltage tolerances of widely used factory equipment, and voltage immunity standards' requirements, it can be concluded that the impact of voltage sags and short interruptions on the GB economy is likely to be as high, or comparable to the share of power quality related losses seen on average in the EU. It is important to note, however, that *no specific large-scale GB-wide study carried out during recent times that has assessed the impact of power-quality issues, particularly voltage disturbances, in the electricity distribution system on the (commercial or manufacturing) industry sectors, has been carried out since [29] was published.*

Furthermore, power-electronic-based equipment, such as that detailed in Table 1 and expected to supply electrical power to digital devices, are also sources of harmonics, unbalance and flicker, which result in supply Alternating Current (AC) voltage waveform deviating from ideally sinusoidal, with rated voltage magnitude and balanced over three phases. A highly distorted supply voltage waveform can cause the malfunction of connected sensitive equipment or may otherwise reduce their expected lifetime, including disturbing power electronic equipment. Although such problems have so far been manageable, or have just begun to become a nuisance for electricity utilities and customers, with the greater proliferation of power-electronic-based loads, such problems, if not accounted for, planned and addressed earlier on, are more likely to become severe.

5. Distributed Energy Resources

'Distributed Energy Resources' (DERs) are defined in [30] as the following: sources and groups of sources of electric power that are not directly connected to a bulk power transmission system. DERs include both generators and energy storage technologies but not controllable loads used for demand response. DER active power (and, optionally, reactive power) control functions are impacted by the connected system's AC supply frequency and voltage (including performance during a system disturbance).

The installed renewable-energy-based generation capacity in the GB electricity distribution system has witnessed a steady increase during recent years, at approximately 4.3 times faster than the electricity transmission system. In 2015, for the very first time since the industrial revolution, the installed renewable energy plant capacity in the distribution system surpassed that of the transmission system [31].

A significant share of the total installed renewable energy-based generation capacity in the GB distribution system in 2015 consisted of PV (46% share) and wind (offshore and onshore, representing a 36% share) based generation [31]. Such resources are intermittent and are increasingly interfaced with the grid via power-electronic-based inverter systems. The power-electronic-based interface lowers system inertia results in a higher Rate of Change of Frequency (RoCoF) in response to disturbances (e.g., following a system fault) [32]. Frequency disturbances in the electricity supply occur frequently, with such disturbances exacerbated (e.g., a risk of desynchronised islands forming where synchronous generators are connected to the distribution networks) as a result of a reduction in system inertia [33]. Furthermore, the same power-electronic-based systems are also sensitive to network voltage disturbances, such as previously discussed voltage sags and short interruptions. Finally, an increasing share of power-electronic-interfaced generation, load and storage systems will result in the increased injections of harmonic currents and other types of waveform distortions. Both the efficiency and performance of such DER and other power electronics connected systems typically deteriorate at low operating powers, as indicated in [34] and acknowledged in [35], where additional low-operating-power test points are stipulated for the performance assessment of DER generation units connected in LV networks.

In order to address the concerns related to increasing frequency disturbances and their severity in the GB electricity networks, the UK National Grid introduced a new two-level Enhanced Frequency Response (EFR) service [36] to bid for and provide a sub-second dynamic frequency regulation during both under-frequency and over-frequency conditions. The EFR service is open to both system Balancing Mechanism (BM) and non-BM providers, with capacities ranging from 1 MW to 50 MW [36]. Most of these EFR service providers, however, have relied on battery-based energy storage technologies. As an example, more than two-thirds of the EFR capacity bidding to the UK National Grid in 2016 was provided by battery-based systems [37]. However, such battery-based systems—which notably use power-electronic-based grid interface systems—are themselves sensitive to severe voltage and frequency disturbances in the electricity supply.

Currently, GB DNOs are also facing the significantly increased loading (and, in some cases, overloading) of aged network components, changes in system fault-levels, and over-voltages in HV and LV networks during normal operation [38-40]. In the case of abnormal operating conditions, such issues can be further exacerbated, causing network operational constraint concerns and placing significant limits on the amounts of generation that can be connected. To address such constraints, there are various options, which include significant levels of infrastructural investments (such as network reinforcement), the use of services from flexible resources (such as battery storage, or distributed generation, or demand-manageable load), or a combination of these options.

From a power systems stability perspective, the transmission and distribution network/system operators must manage (i.e. balance) the intermittency of renewable generation. These challenges can be intensified by the possibility of generation-tripping or otherwise malfunctioning during the system voltage and frequency deviations.

Currently, network operators are responsible for the coordination of voltage and frequency control settings between DERs and the connected electricity distribution system. The latest DER interconnection and interoperability standard, IEEE 1547-2018 [41], specifies the voltage and frequency control capabilities for DERs, but leaves the coordination of voltage and frequency control settings with the network operators, particularly at the distribution network level.

5.1. Impact of Electricity Supply Disturbances on Distributed Energy Resources

Voltage sag and short interruption immunity requirements for the distribution system connected generation—which are commonly referred to as 'fault ride-through capability'—are overlaid with typical system protection settings and two typical MW-scale Wind Turbine Generator (WTG) types' protection settings, as illustrated in Fig. 2. Voltage disturbance tolerances of typical PV generators based on tests are given in [42].

Furthermore, although the high penetration of DGs can elevate distribution system operational voltage and, therefore, reduce the severity of voltage sags and interruptions propagated from the transmission network, an under-voltage with significant duration (for example: lasting longer than 500 ms) within the network, or at a lower voltage level (where the DG is connected), could cause sustained voltage sags or short interruptions, subsequently resulting in the trip or malfunction of sensitive DG equipment, particularly those with a power-electronics-based grid interface.

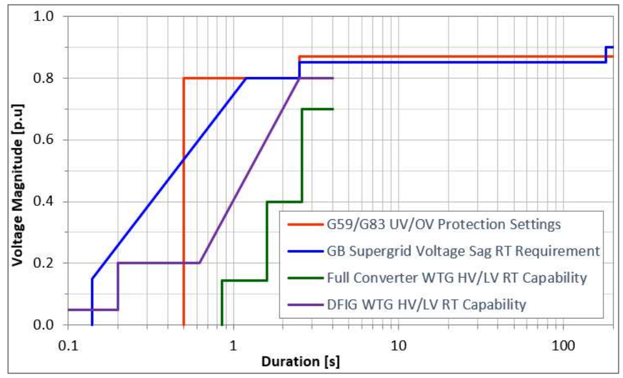


Fig. 2. *GB voltage-magnitude-duration Ride Through (RT) and G59/83 protection requirements for DG [9, 43, 44] and RT capabilities of widely used WTG types (i.e. Doubly Fed Induction Generator (DFIG) and full converter) [45].*

6. Electricity Distribution System

The GB electricity distribution system, which begins at 132 kV Grid Supply Points (GSPs) in England and Wales and at 33 kV GSPs in Scotland, was historically designed to distribute energy from the transmission system to dispersed loads (including large-, medium- and small-scale energy consumers) connected to: 132 kV or 33 kV; 33 kV or 11 kV or 6.6 kV; and 400 V distribution voltage levels, respectively.

6.1. Reliability Performance

As mentioned, the GB electricity supply reliability is assessed using CI and CML indices, which are considered for supply interruptions longer than three minutes (also referred to as Sustained Interruptions in [19]) and taking into account all electricity customers, irrespective of their size, voltage connection, tariff, or energy consumption.

A comparison of these indices for the US, GB, the city of London (via London Power Networks, LPN), and Singapore electricity networks is shown in Fig. 3 (GCI ranks are also given in the figure caption). The reliability performance of GB networks has clearly improved and continues to improve with the revenue incentive framework setup by OFGEM. Such incentives have led the DNOs to achieve major reliability improvements (i.e. 48% lower CIs and 58% lower CMLs since 2001–02), while electricity network costs fell by 17% [46] between the time of privatisation and 2014. Although the GB electricity network reliability performance, when compared to the US, has significantly improved over the years, the reliability performance of electricity distribution networks in London is still behind other major cities, such as Singapore, Tokyo, New York and Hong Kong [47].

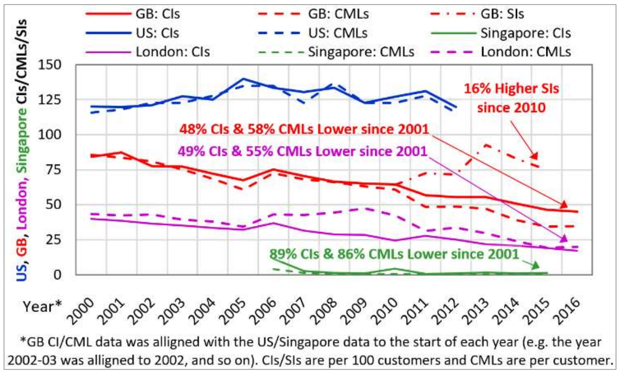


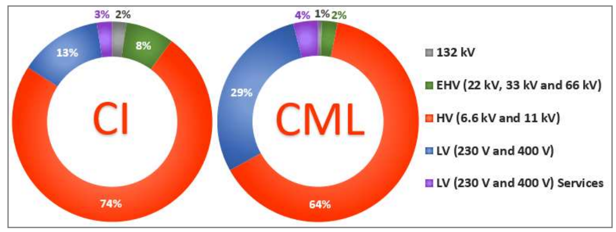
Fig. 3. *Comparison of the US, GB, the city of London, and Singapore average CIs/SIs/CMLs [48-53]. (Note: The 2017–18 World Economic Forum's Quality of Electricity Supply ranking, per [54], for the US, UK, and Singapore are 26th, 12th, and 3rd, respectively. The GB DNO SIs data, which are part of OFGEM's Annual Electricity Distribution Quality of Service Reports, was obtained for 2010-15 by the authors here from OFGEM with GB DNOs' consent.)*

While CIs and CMLs have improved in GB, there has been an increase in short interruptions (i.e. 16% at the 2015 mark from 2010) (see Fig. 3). However, the actual numbers of short interruptions may be much larger due to questions over the robustness of the short interruptions data, as common recording and reporting practices have not been fully developed in the same way as for the current CI- and CML-based reporting.

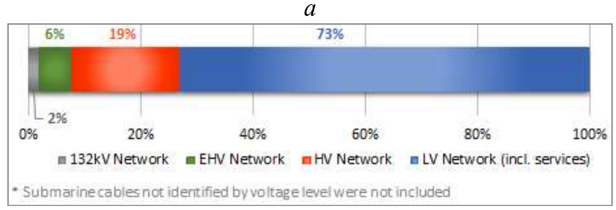
The rise in the number of short interruptions is not only owing to the lack of short-interruptions-based regulatory outputs and financial incentives for DNOs, but also as a result of the strategies the GB DNOs are currently applying to manage CIs and CMLs: typically, approximately 80% of all such incidents affecting overhead lines are of a transient nature (per a GB DNO's Overhead Protection Policy document in [55]). A key approach in which the CIs and CMLs have been tackled in GB for transient faults in overhead distribution networks is to replace fuses on tee- or spur-circuits with auto-sectionalisers. With such an approach, the DNOs now no longer see transient-faults-related fuse operations, which would result in long interruptions and subsequently require the DNO line crew to visit the faulted site and accordingly search for a problem that is no longer there. Although such an approach helps to meet the objectives of improving reliability (i.e. reducing number and duration of long interruptions), the replacement of fuses with auto-sectionalisers (used with up-line circuit breakers or reclosers) would significantly increase number of short interruptions, because auto-sectionalisers—not being fault interrupters—cannot and, therefore, do not contain or interrupt faults on the tee- or spur-lines they supply. As a result, all customers connected on to and via the main feeder, as well as on the parallel feeders, are now affected and experience short interruptions and voltage sags. Accordingly, it may be concluded that the use of more sophisticated (automated) technologies, such as auto-sectionalisers in the distribution networks, worked well in the conventional energy system, though such an approach is not well suited to a modern electricity grid, particularly with large proportions of sensitive generation and DERs connected to distribution feeders.

6.2. Reliability Performance to Fault-Rate Correlation

The shares of average annual CIs/CMLs and average annual equipment fault rates by voltage levels in GB distribution networks are given in Fig. 4(a) and Fig. 4(b), respectively. The data in these figures show that, although only approximately 19% of all faults in the GB distribution system originate in the HV network, these faults contribute to a significant share of the overall GB reliability performance (i.e. 70% in CIs and 60% in CMLs). However, if the same reliability metrics (CIs and CMLs) were to be redefined to include short interruptions and a count of related customer minutes lost, especially due to faults in the HV network, the impact on GB electricity customers would then likely be much greater.



a



b

Group Demand (GD) Classes ⇨	Class A (LV) GD ≤1 MW	Class B (HV) 1 MW < GD ≤ 12 MW	Class C (EHV) 12 MW < GD ≤ 60 MW	Class D (132 kV) 60 MW < GD ≤ 300 MW
Group Demand Restoration Time ⇨	Restored in Repair Time	+ Restored in < 3 Hrs	+ Min of {GD minus 12 MW and 2/3rd of GD} restored in 15 mins	+ GD minus ≤20 MW restored immediately (i.e. < 1 min)

c

Fig. 4. *Reliability performance to fault-rate correlation* ***(a)*** *GB Average CI/CML share by voltage levels in 2008-09 [56],* ***(b)*** *2001–15 GB avg. fault rate share by voltage levels [57],* ***(c)*** *ENA P2/6 GB Group Demand classes (with their typical supply voltages) and security of supply minimum demand and restoration time requirements following a first network circuit outage [12].*

Other things being equal, the impact on reduced network reliability will increase with faults occurring higher up the feeders and at higher voltage levels. As an example: i) the impact of a fault higher up on the feeder will be much greater than the same fault on a down-feed tee, or a spur feeder, especially when a fuse-link, a sectionaliser, or a single-phase recloser can clear the fault on that spur line; ii) the impact of an HV network fault will be greater than the same fault in an LV network. Both are mainly the consequence of a much higher number of customers impacted by the fault.

As shown in Fig. 4(c), distribution networks at voltages above 11 kV and up to 132 kV are required in order to be sufficiently automated and with appropriate redundancy/reconfiguration capabilities and alternative supply connections, which allows them to satisfy fast restoration times as per ENA Engineering Recommendation

(ER) P2/6 on Security of Supply [12]: the distribution Group Demand Class C (with over 12 MW and up to 60 MW of load, typically connected to EHV networks) and Class D (with over 60 MW and up to 300 MW of load, typically connected to 132 kV networks) are required to be restored in 15 minutes and 1 minute, respectively.

In contrast, *HV networks, as a result of lower supply restoration requirements (e.g., the maximum restoration time for Group Demand class B, which is typically supplied by HV networks, is three hours), give rise to the highest share of existing GB CIs and CMLs.* Unlike the EHV networks at 22 kV and above, which are typically driven by the ER P2/6 requirements, the HV networks and their design and operation will be driven more to improve performance under OFGEM's reliability incentive mechanism.

6.3. Power Quality Performance

At the present time, there is no recognised GB electricity utility-wide power quality performance evaluation or reporting scheme, whether voluntarily undertaken and published by GB electricity utilities, or otherwise required by OFGEM, which can be used by these utilities to improve voltage quality beyond long (sustained) interruptions (or CIs)—and SIs, if incentivised in the future (for example, in RIIO-ED2)—in their networks, particularly regarding instantaneous and momentary voltage sags. Such monitoring or reporting work by the electricity utilities, or requirement by OFGEM, also does not exist for other power quality parameters, such as voltage unbalance, harmonics, and voltage fluctuation (e.g., flicker). As mentioned before, *the evaluation and regulation of voltage quality in GB remains to be within the basic requirements from [58] and GB is currently behind a number of other EU countries that not only report on voltage quality, but also define additional and usually more stringent requirements to these in [58], as discussed in [59].*

7. Electricity Smart Meters

The UK Government aims to have every home and small business be offered a smart meter by the end of 2020; the government, therefore, introduced the set of Smart Metering Equipment Technical Specifications (SMETS), which detail the minimum physical, functional, interface and data requirements of Electricity Smart Metering Equipment that an electricity Supplier is required to install [60].

The Version 2 of the SMETS (referred to as SMETS2), which will support 'variant' electricity meters, including auxiliary load control switches, boost buttons, multiple measuring element meters and polyphase supplies [61], came into effect in September 2018. *Although the SMETS2 specifies the much required logging of voltage-quality-related events as part of the smart meter functional requirements [60, 62], the technical specifications falls short of including the frequency-based event logging functionality and monitoring of other important power quality parameters, such as voltage unbalance, harmonics, and voltage fluctuations (e.g., flicker).*

8. Distribution System Compatibility and Interoperability

According to IEC 61000-3-7 Technical Report [63], electromagnetic compatibility is a condition of the electromagnetic environment such that, for every phenomenon (including an electricity supply voltage disturbance), the disturbance emission level is sufficiently low and immunity levels are sufficiently high, so that all devices, equipment and systems operate as intended. This is illustrated in Fig. 5, using a statistical approach for representing variations between site-specific disturbance levels and equipment immunity levels. In an ideal compatibility scenario, there should not be an overlap between the site/system disturbance level and immunity probability density curves, which are illustrated by vertical lines in Fig. **5**. In practice, however, and as also shown in Fig. 5, some degree of overlap between the probability densities may exist, typically leading to equipment malfunction.

As stated in [63], 'Planning levels are specified by the system operator or owner for all system voltage levels and can be considered as internal quality objectives of the system operator or owner and may be made available to individual customers on request'. To set momentary and instantaneous voltage-sag- and short-interruption-based power quality planning levels, these events must be measured and reported. Reasonable planning levels may consider customer electrical load equipment immunity, the local or widely used equipment immunity test levels and immunity standards, while also considering the cost of events using an economic assessment.

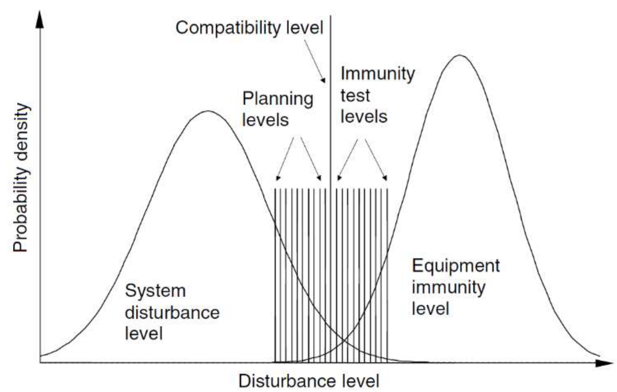


Fig. 5. *Illustration of electromagnetic compatibility concept from [63].*

The main instrument and basis for voltage quality regulation in the EU is the BS EN 50160 Std [58]. It discusses the main characteristics of supply voltages at a network user's supply terminals in public low voltage, medium voltage, and high voltage AC electricity networks under normal operating conditions, such as steady state distribution network operating voltage, harmonics, flicker and voltage fluctuations. This standard acknowledges that supply voltage characteristics are subject to variations during the normal operation of a supply system, e.g., due to large changes in load, disturbances generated by certain equipment, and occurrence of faults (which are mainly caused by external events). The standard does not apply to abnormal operating conditions, e.g., temporary network reconfigurations required to provide supply during maintenance and faults, and it excludes exceptional events. Exceptional events include but are not limited to: major natural events ('force majeure'), such as extreme weather conditions, floods, landslides, earthquakes, avalanches, fires, hurricanes and cyclones, as well as major human-caused events, such as sabotage, vandalism, terrorism, acts of war, strike action, and social unrest. Further discussion of exceptional events is provided in Section 9.4.

Although equipment-based voltage-immunity requirements exist in some standards (e.g., [64], SEMI F47-0706, ITIC/CBEMA, IEC 61000-4-11 [16], etc.), they remain focused primarily on electrical loads and their applications in niche industries (e.g., semiconductor manufacturing, IT, etc.). Various manufacturing processes may have a Process Immunity Time (PIT), which is the maximum time between the instance of electricity supply disturbance occurrence and the instance at which the process will be interrupted, because the disturbance trips some process equipment responsible for keeping at least one of the critical process parameters within the acceptable range of variations [17]. The PIT concept considers that the malfunctioned equipment might or might not restart (automatically or via manual intervention), upon the end of disturbance and electricity supply recovery to its normal operation and resume the process within its required tolerances. The lower the PIT value, the lower the time available for the malfunctioned equipment, following electricity supply disturbance, to resume the process within the process's tolerances. Although the PIT concept allows for a realistic evaluation of the impact of voltage sags, *the equipment immunity standards mentioned in this paragraph have not accounted for equipment PIT capability aspects.*

Where utility measurements are not available, for example, prior to broad installation of power-quality-based smart meters and other metering/monitoring equipment across the network, voltage sag and interruption distribution network performance and customer geographic areas with a high likelihood of equipment trips can be estimated using probabilistic approaches based on known network protection settings (examples of such approaches are detailed in [65, 66]).

Interoperability, which is defined as the capability of two or more networks, systems, devices, applications or components to exchange and readily use information (securely, effectively, and with little or no inconvenience to the user) [63], is a step further to equipment compatibility, allowing for a greater coordination of operational capabilities and functionalities between system components to deliver better services to electricity customers and network users.

The CIGRE, CIRED, and UIE Joint Working Group (JWG) C4.110 aimed at simplifying and harmonising voltage immunity and related testing standards. The working group proposed an equipment labelling approach [17], based on the following five voltage immunity classes (in the order of decreasing voltage sag immunity requirements): Class A, B, C1, C2, and D, which are then combined with equipment performance levels, i.e. full (disturbance ride-through) operation, (post disturbance) self-recovery, and (post disturbance) assisted-recovery. In spite of the fact that the approach proposed in [17] considers existing voltage sag immunity standards, such as IEC-61000-4-11, IEC 61000-4-34 and SEMI F47-0706 [61], the proposed labelling was not widely adopted by the industry, standard bodies, or national/regional authorities.

The current IEEE 1547-2018 Std [41] focuses on the interconnection and interoperability of distributed energy resources with associated electric power systems interfaces. The standard specifies and harmonises (based on distributed generation requirements in Germany and some US states) the physical and communication requirements for interconnection of DERs (e.g., DGs and energy storage, but not electrical load). The standard—with an increasing level of disturbance ride-through and active control capability requirements—specifies: i) a three-level abnormal operating performance requirement, via Categories- I, II, and III; and, ii) a two-level reactive-power capability and voltage control requirement, via Categories A and B.

The ENA EREC G5/5 draft (in [67]), which, when finalised, will apply to the UK electricity transmission and distribution networks, is an indication of the ongoing revision of the ENA EREC G5/4-1 (in [68]), harmonised with several IEC emission standards (e.g., IEC 60050(161), IEC/TR 61000-3-6, IEC/BS EN 61000-3-2, 61000-3-12, etc.). It considers existing and future harmonic, sub-harmonic and inter-harmonic issues due to the anticipated increase of the power-electronic-based equipment and inverter-interfaced generation/storage systems. For example, the current draft of ENA EREC G5/5 includes harmonic assessment and compliance up to the 100th harmonic order. The draft standard also increases clarity on the consideration of waveform distortions which may cause equipment related compliance issues, such as short-duration bursts, fluctuations, or voltage notches, for example, and advocates for a more granular approach to the specification of harmonic planning and compatibility levels for all voltage levels. Such changes aim to increase the overall likelihood of compatibility between electricity network and customer equipment in terms of the discussed power quality aspects. The latest ENA EREC G59 (in [43]), which notably provides guidance on the connection of generating plants to distribution systems, continues to include explicit mandatory requirements for all new DG to comply with the ENA EREC G5 limits.

Currently, there is not a GB-wide survey, benchmarking or reporting scheme that quantifies the voltage and frequency disturbance performance metrics in GB distribution networks. Such metrics could allow for existing or future electricity customers, specifically those investing in Industry-4.0-based technologies, and equipment suppliers to evaluate GB electricity supply performance against the tolerances of the equipment they may choose to use, or to manufacture.

Smart meters, capable of measuring electrical supply power quality indices, may be used to capture momentary voltage and frequency disturbance data in measurements implemented at strategic locations (e.g., at substation Point of Common Coupling, PCC, busbars) within the distribution networks in GB. Capturing this data would require adequate IT infrastructure for DNOs and/or the Data Communications Companies (DCCs) that collect and consolidate the smart metering data. Such data can be used to quantify aggregate power quality performance data by location, which can be then used to evaluate equipment immunity to these disturbances. As an example, voltage RMS variation events could be plotted against the ITIC/CBEMA (or other equipment-specific) voltage-tolerance curves [69]), or presented via voltage sag tables [17, 58, 70], or voltage sag coordination charts [71]. Other power quality parameters, such as voltage unbalance, harmonics, and voltage flicker, representing aggregated performance over a suitable observation period (e.g., weekly) could also be presented. These and similar approaches to evaluating the power quality performance of supplying networks could then allow for the appropriate selection of various applicable local/(inter)national network, DER, and equipment voltage-frequency-immunity or -control standard requirements, or performance class/categories, as detailed above in this section.

The provision of a GB-wide electricity distribution system compatibility and interoperability evaluation framework is vital to enable the setup of the next generation of industries driving increased productivity, especially if GB is to be one of the most competitive places in the world to start, or to grow a business.

9. GB Electricity Regulation

A long-term implementation of appropriate regulation of performance of DNOs/DSOs, which might be incentive-based, is very important for driving improvements to electricity supply security, reliability and power quality, for which customers should pay an acceptable, price. This is a core element of the energy regulator's principal duty: to protect the interest of existing and future customers at a time when the current and prospective UK economy, including the anticipated digital economy, will increasingly use electricity as a primary/secondary fuel source.

9.1. Electricity Reliability

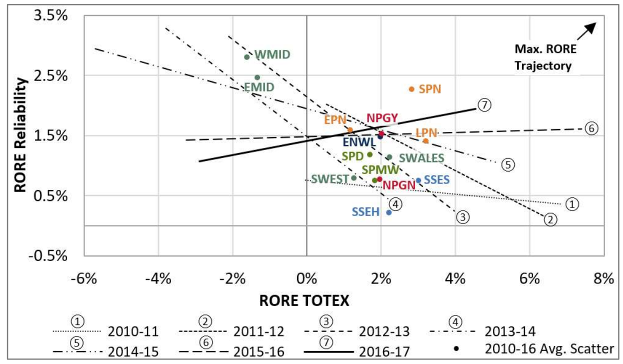
Since the privatisation of electricity in 1989, OFGEM and its predecessors have implemented price control incentive arrangements, which have led to DNOs successfully improving reliability while at once reducing the cost of electricity to customers. How this reliability improvement was achieved, how it compares to other countries'/cities' electricity networks, how it was measured, and the implications of this on GB electricity customers and productivity, are discussed next.

9.1.1. DNO RORE TOTEX-Reliability Performance: In the fifth electricity Distribution Price Control Review (DPCR5) for the period spanning 2010–2015, OFGEM introduced the Return on Regulatory Equity (RORE) metric as a measure of overall financial performance. The RORE is the base return-on-equity, plus additional incentive rewards or penalties expressed as a percentage of the regulatory asset base.

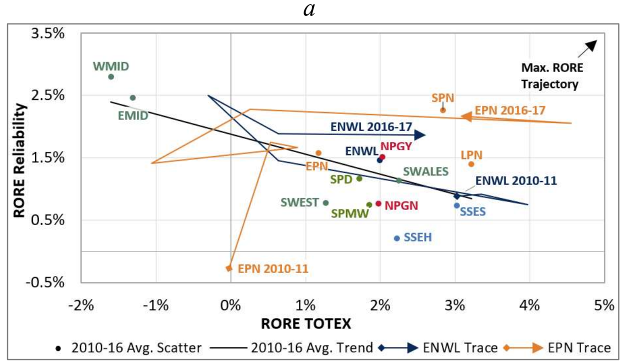
The additional RORE earnt through the total expenditure (or simply, the TOTEX) and the reliability incentives by all GB DNOs from 2010–11 to 2016–17 are shown in Fig. 6(a). The figure also shows the RORE TOTEX-reliability trend line for all GB DNOs for each year spanning 2010–11 through to 2016–17. The trajectory to maximise the TOTEX and the reliability incentives is marked in Fig. 6(a).

The year 2010–11 was the first year of DPCR5 with new CI and CML targets, TOTEX allowances, and changes to the TOTEX incentives. There were delays for some DNOs initially in implementing their investment programmes; however, DNOs ramped up their condition-based asset replacement programmes and investments in reliability improvements throughout the period. As these investments fed through to improved CI and CML performance with a lag, DNOs initially saw underspends against their respective TOTEX allowances with relatively small reliability gains; following this, the TOTEX increased, with smaller reliability improvements at first, followed by a larger reliability improvement seen later. The TOTEX-reliability relationship was initially relatively flat, then it steepened or improved with time, in each regulatory year, as can be seen in Fig. 6(a).

In the final years of the DPCR5, the effective incentive to improve reliability weakened, as better performance would feed through to tighter performance targets for later years. The year 2015–16 was the first year (or the beginning of a new cycle) of RIIO-ED1, with new reliability targets and TOTEX allowances, again resulting in a flatter RORE TOTEX–reliability relationship.



a



b

Fig. 6. *Plots showing the average RORE TOTEX-Reliability incentive performance for all GB DNOs during 2010–17* ***(a)*** *Trend lines for each year (identified via ① to ⑦) from 2010–11 to 2016–*17 (based on data in [50, 51]), **(b)** *Example DNOs' (ENWL and EPN) traces from 2010–11 to 2015–16 (based on data in [50, 51]).*

In Fig. 6(b), the same average RORE TOTEX-reliability data points are shown for each DNO, as in Fig. 6(a), but with traces of how example DNOs' (ENWL and EPN) RORE incentive performance have moved in each year spanning 2010–11 to 2016–17.

As shown in Fig. 6(b), ENWL, during the period 2010–16, has moved parallel to the trend line over the years, with increased TOTEX associated with improved reliability performance, and vice-versa; this was also the pattern witnessed for most DNOs with the exception of EPN and two other UKPN DNOs (i.e. SPN and LPN), both of which have broken the trendline and achieved improvements in both TOTEX and reliability incentive performance. To the best of the knowledge of the authors of this paper, *these* *interrelationships between the TOTEX and reliability components within the overall RORE have not previously been explored to understand the relationship between reliability improvements and related expenditures.*

9.2. Customer Satisfaction

OFGEM's customer service incentive, the Broad Measure of Customer Satisfaction (BMCS), was introduced in 2012–13 for electricity DNOs to deliver good customer service. The BMCS has the following three components: the Customer Satisfaction Survey, Complaints Metric and Stakeholder Engagement Incentive. The scores (on a scale of 1 to 10) of these BMCS components for GB DNO groups in 2016-17 are shown in Fig. 7: higher scores for Customer Satisfaction and Stakeholder Engagement are better, while a lower score for the Complaints Metric is better.

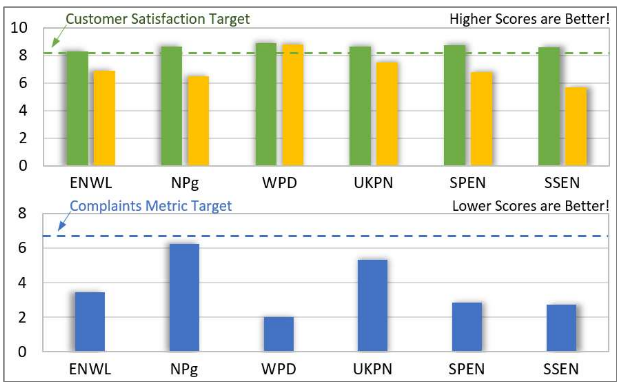


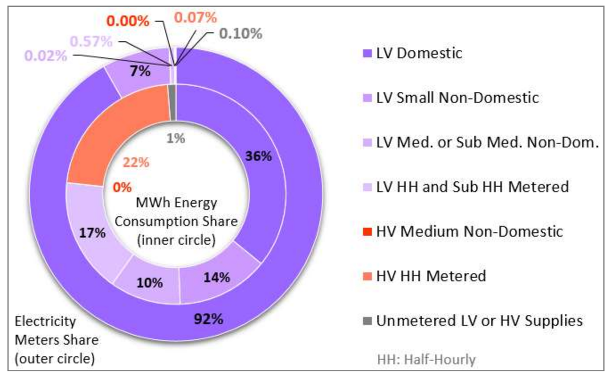
Fig. 7. *2016–17 BMCS component scores averaged per GB DNO group [51].*

The average Customer Satisfaction score (i.e. 8.7) of GB DNO groups in 2016–17 has exceeded the OFGEM's target (of 8.2) by around 6.1%, while the average Complaints Metric score (i.e. 3.7) of GB DNO groups during the same year beat OFGEM's 2016–17 target of 8.33 by 55.4%. These results are good for GB electricity customers. However, based on the DNOs' 2016–17 performance, OFGEM's target score of 8.2 for complaints was much easier to achieve, with the average Complaints Metric score of GB DNO groups notably 3.7 points; however, it was still away from a zero value (i.e. receiving no complaints), meaning there is always an opportunity for further improvement.

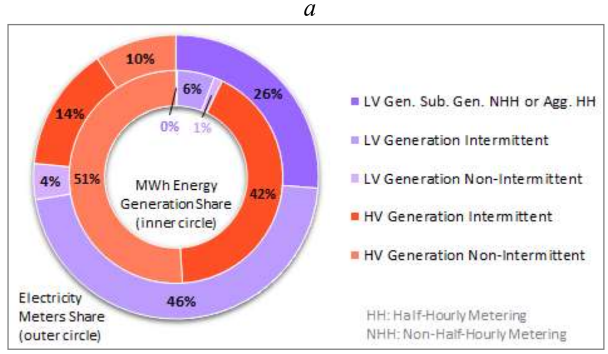
9.3. Treatment of Customers in the BMCS and Reliability Incentive Mechanisms

In 2015, based on the data in [72], domestic electricity consumption was 37% of the total GB electricity consumption, while the average annual domestic electricity consumption per meter was 3.9 MWh, with a median of 3.2 MWh. In the same year, the non-domestic electricity consumption was 63% of the total GB electricity consumption, while the average annual non-domestic electricity consumption per meter was 76.8 MWh, with a median of 8.7 MWh.

The electricity consumption during this period (i.e. in 2015) was based on 30 million meters in operation; among these meters, around 27.6 million (or 92%) were in the domestic sector, with the remainder of 2.4 million (or 8%) in the non-domestic sector [72]. Fig. 8(a), based on the GB DNOs' 2018–19 charging data (accessed via [73]), shows that although the HV connected load represents about 22% of the total share of the electricity distribution consumption, the actual number of HV connected electricity meters it corresponds to is less than 0.1% of the total (i.e. an HV MWh load consumption share to per HV meter share ratio of 314.3 (or 22%/0.07%)); similarly, the 41%, i.e. sum of 17%, 10% and 14% values in Fig. 8(a), corresponding to share of distribution electricity consumption by the LV non-domestic load, pertains to a 7.6%, i.e. sum of 7%, 0.02% and 0.57% values in Fig. 8(a), share of electricity meters.



a



b

Fig. 8. *Load and generation distribution by customer types;* ***(a)*** *Electricity distribution load and meters share by tariffs [73],* ***(b)*** *Electricity DG and meters share by tariffs [73].*

However, the OFGEM's BMCS mechanism in GB—much like the reliability measure mechanism—treats all electricity customers, irrespective of their load profile, size or their voltage connection, the same. As it stands, the BMCS is heavily focused, and therefore biased, towards the GB domestic sector, so it underrepresents the GB non-domestic, or industry sectors. A similar concern was also highlighted in [74] in respect of the interruption incentive scheme. Due to the disproportionate representation of industry and other non-domestic customers based on their numbers and on their energy consumption, the 'voice' of these customers via the existing BMCS mechanism is not effectively captured.

The ratio of the energy generation share (sum of 42% and 51% values in Fig. 8(b)) to meter share (sum of 14% and 10% values in Fig. 8(b)) of 3.9 (or 93%/24%) for HV-connected DG is lower than the HV demand ratio of energy consumption share to meter share. This means that *the HV connected DG customers are better represented among all*

DG customers than the HV connected distribution load consumers among all distribution-connected load consumers.

Under the current GB DNO reliability incentive mechanism, all customers—irrespective of whether they are consuming or generating electricity and regardless of their tariffs—are treated the same. The effect [74] is that reliability incentive mechanism '…will tend to encourage DNOs to provide better reliability to consumers for whom it is relatively cheap to provide additional security of supply (such as those in urban areas) and less to customers in areas in which it is more costly to enhance security of supply (such as those in rural areas)'. The reliability incentive mechanism—which notably has no weighing of customer tariff types, connection capacity, voltage level or energy usage—also underrepresents the non-domestic customers; while these customers may be able to address reliability issues themselves, it may, however, be more efficient to address these issues with the DNOs in a coordinated manner.

With greater volumes of DG being connected to the network, the network availability for DG customers, or connectees, becomes increasingly important, as they will have direct financial losses associated with the network outages. Although a DG network unavailability payment was included in the rules of the DPCR5 DG incentive, and later dropped when the main DG incentive was removed, it is worth reconsidering an incentive for these connectees, either as part of the interruptions' incentive scheme, or as part of the separate parallel incentive scheme. Short interruptions are also becoming much more relevant, as with large volumes of DG scattered across distribution feeders, it is more likely they will trip some of the DG units.

9.4. Exceptional Events in the Reliability Incentive Mechanism

One important aspect of OFGEM's reliability incentives is the treatment of periods of severe weather and other exceptional events. OFGEM's severe weather mechanism removes the impact of extreme weather periods, such as storms, from the DNOs' performance under the reliability incentives, provided there is an increase of more than eight times the daily mean number of faults during these periods at HV and above. The one-off exceptional event mechanism removes certain incidents for which DNOs have limited ability to prevent or reduce the impact of their occurrences on reliability performance (such as wilful damage, or theft of DNO's assets). This is again subject to pre-defined thresholds for evaluating the impact of these events [75].

One of the effects of climate change is an increase in the occurrence of severe weather events, such as lightning, high winds and flooding, with the DNOs also carrying out investments to harden their networks and improve resilience against these events. Accordingly, the ability of DNOs to withstand such events and quickly restore supply to interrupted customers is not only an important aspect during the evaluation of their reliability performance but also something that matters to customers.

It is, therefore, important that OFGEM revisits the thresholds and definitions of exceptional events for RIIO-ED2 and further considers which incentives should apply in relation to such events to encourage improvements in resilience of electricity networks as one of the critical infrastructures.

10. Policy Implications and Recommendations

No individual electricity industry party can deliver the electricity infrastructure and equipment that will fulfil the UK Government's vision, but with a collaborative effort of all involved electricity industry parties, this is possible.

Based on the sensitivity of existing and new load/DG, it may be concluded that OFGEM's current approach to quantify electricity distribution network performance should move from CI and CML alone, through to the full inclusion of short interruptions and other power quality metrics. This is especially important in the network areas that include loads and generation of national economic importance. There is an opportunity for the appropriate metrics to be reviewed as part of the consultations on the RIIO-ED2 framework for electricity distribution that will apply from 2023 and for incentives to be extended to short interruptions, including the impacts on the increasing levels of distributed generation.

The GB DNOs could deploy currently available and proven technologies that allow for a rapid electricity network self-healing following faults, using advanced switchgear, communications, centralised or distributed intelligence-based systems, and distributed voltage control devices, to deliver the needed secure, reliable and high-quality electricity infrastructure.

Furthermore, the electricity standard bodies, working with equipment manufacturers, electricity customers, and electricity network operators, should setup easy-to-use standardised procedures to assess equipment sensitivity (e.g., equipment voltage event immunity labels). Area-based reliability and power quality performance data could be made available by the DNOs and then used by electricity customers to ascertain the target levels of sensitivity of their electric equipment—again via voltage event immunity labels, for example.

A voltage sag and short interruption mitigation solution that ensures system-wide costs are low, with good voltage sag-interruption performance and productivity, is typically one where mitigation solutions are implemented in a distributed manner among affected industrial/service customers and the supplying electricity utility [76]; however, such consideration may exist at a transmission-planning level, with the need for a similar one in the distribution networks growing, especially in light of ongoing and emerging developments related to the digital economy and Industry 4.0.

The international JWG C4.110 undertook a comprehensive investigation, summarised in [17], into the existing compatibility levels between customer installations and electricity supply and proposed to various electricity industry stakeholders, including electricity regulators and network operators, several recommendations [77], as listed below:

- The occurrence of voltage sags is part of the normal operation of any power system;
- Monitoring and recording of voltage sags is needed;
- Regulators should provide the incentives to facilitate voltage sag monitoring by network operators;
- Voltage sags are the main concern for industrial customers, after reliability, and may result in serious economic loss for many industrial customers;

- Mutual understanding of origins and consequences of voltage sags is an essential basis for jointly addressing the compatibility between the network and the industrial installation; and
- Customers need data on number and severity of voltage sags to improve immunity of their equipment.

In addition to accounting for the JWG C4.110 recommendations listed above, in delivering the UK Government's 2017 Industrial Strategy from an electricity industry point-of-view, the authors of this paper, as based on the presented arguments, also recommend the following, specifically in the electricity distribution context:

- Promote the standardisation of electricity supply-related definitions of security of supply, reliability and power quality;
- Promote the need for standards dealing with the coordination of voltage and frequency control settings between DERs and the electricity distribution systems to which these DERs are connected;
- Include frequency-based event logging functionality as one aspect of the smart meter's functional requirements in future SMETSs;
- Undertake a new customer research upfront that will inform the shape of the previous RIIO-ED1 and next RIIO-ED2 frameworks, accounting for types of customers and connections and different aspects of reliability in a more representative manner;
- Commission a GB-wide power quality survey, which should specifically include capturing occurrences of voltage sags and their magnitudes and durations in electricity distribution networks. The survey should also capture information on the sag-related costs incurred by commercial and industrial customers, to inform whether the additional reporting requirements should be included in this area for RIIO-ED2 and beyond. Such a survey could also include capturing customers' cost-of-downtime and impacts due to other power quality issues, such as harmonics, voltage unbalance, and voltage fluctuations;
- Review the weighting of customers/connectees (e.g., the UK factories, commercial customers, etc.) in the interruption incentive scheme and consider whether network availability incentives for DG are needed;
- Extend the DNO financial incentive mechanism to account for short interruptions, based on the measured improvements in DNO performance; correlate short interruptions with voltage sags, as both are part of evaluating network power quality performance;
- Review the exceptional events arrangements in RIIO-ED2 and consider what exceptional event incentives should apply to take account of climate change and adaptation to it by the DNOs and customers' needs for resilience;
- Develop a BMCS measure and reliability incentives that fairly account for different size load and generation connectees; this could consider the opportunity of separating the BMCS by MWh consumption, or by generation classes, or by peak demand/generation, or by connection voltage level;
- Approach process of performance evaluation of distribution electrical supply with a combined view of security of supply, reliability, and power quality—moving towards resiliency—rather than in isolation of one another, where the motivation is to reduce/optimise system-wide costs and to help to maintain, if not to increase the productivity of manufacturing; and
- Specify appropriately targeted BMCS surveys, which should work together with enhanced reliability metrics.

11. References

[1] 'Building our Industrial Strategy: Green Paper', (Department for Business, Energy, & Industrial Strategy, UK Government, 2017), pp. 5-17

[2] 'Gross Domestic Product, Preliminary Estimate: Jan to Mar 2017', https://www.ons.gov.uk/economy/grossdomesticproductgdp/bulletins/grossdomesticproductpreliminaryestimate/jantomar2017, accessed 20th July 2017

[3] 'Energy Consumption in the UK (2016 Data Tables - Table 1.04)', (Department for Business, Energy & Industrial Strategy, UK Government, 2016)

[4] 'Future Energy Scenarios in Five Minutes (Data Workbook) - System Operator', (National Grid plc., 2018, 2 edn.), pp. 5.1-ES2

[5] 'Annual Manufacturing Report 2017', (Hennik Research, 2017), pp. 9-11

[6] 'ENA Open Networks Project', http://www.energynetworks.org/electricity/futures/open-networks-project/, accessed 20th July 2017

[7] Schwab, K. and Sala-i-Martín, X.: 'The Global Competitiveness Report 2016-2017', (World Economic Forum, 2016)

[8] Schwab, K.: 'The Global Competitiveness Report 2018', (World Economic Forum, 2018), pp. 9-14

[9] 'The Grid Code - Glossary & Definitions', (National Grid Electricity Transmission plc, 2018), pp. 1-70

[10] 'National Electricity Transmission System Security and Quality of Supply Standards - Terms and Definitions', (National Grid Electricity Transmission plc, 2017), pp. 54-74

[11] 'The Distribution Code - Distribution Glossary and Definitions (DGD)', (Energy Networks Association Limited, 2018), pp. 8-23

[12] ENA EREC P2/6: 'Security of Supply', 2006

[13] 'Security, Quality, Reliability, and Availability: Metrics Definition: Progress Report', (EPRI PEAC Corporation, 2005, 1008568 doc. no.), pp. 6-6

[14] 'Statutory Security of Supply Report', (Department for Business, Energy & Industrial Strategy, UK Government, 2018, HC 1644 doc. no.), pp. 6-6

[15] 'RIIO-ED1 Regulatory Instructions and Guidance: Annex F – Interruptions', (OFGEM, UK Government, 2015, 1.0 edn.), pp. 20-48

[16] IEC 61000-4-11, ed. 2.1: 'Electromagnetic compatibility (EMC) – Part 4-11: Testing and Measurement Techniques – Voltage Dips, Short Interruptions and Voltage Variations Immunity Tests', 2017

[17] 'CIGRE/CIRED/UIE JWG C4.110: Voltage Dip Immunity of Equipment and Installations', (CIGRE, 2010, TB412 doc. no.), pp. 12-46

[18] 'RIIO-ED1 regulatory instructions and guidance: Annex A – Glossary Version 1', (OFGEM, UK Government, 2015)

[19] 'IEEE Recommended Practice for Monitoring Electric Power Quality', IEEE Std 1159-2009 (Revision of IEEE Std 1159-1995), 2009, pp. c1-81
[20] '2016/17 UK Manufacturing Fact Card', (EEF Ltd, 2017)
[21] Kundu, S. and Hiskens, I.A.: 'Overvoltages due to Synchronous Tripping of Plug-in Electric-Vehicle Chargers Following Voltage Dips', IEEE Transactions on Power Delivery, 2014, 29, (3), pp. 1147-1156
[22] Djokic, S.Z., Milanovic, J.V., and Kirschen, D.S.: 'Sensitivity of AC Coil Contactors to Voltage Sags, Short Interruptions, and Undervoltage Transients', IEEE Transactions on Power Delivery, 2004, 19, (3), pp. 1299-1307
[23] Djokic, S.Z.*, et al.*: 'Sensitivity of AC Adjustable Speed Drives to Voltage Sags and Short Interruptions', IEEE Transactions on Power Delivery, 2005, 20, (1), pp. 494-505
[24] Djokic, S.Z.*, et al.*: 'Sensitivity of Personal Computers to Voltage Sags and Short Interruptions', IEEE Transactions on Power Delivery, 2005, 20, (1), pp. 375-383
[25] Short, T.A.: *Electric Power Distribution Handbook*, (CRC Press, 2014, 2nd edn.)
[26] 'Power Quality Impacts on Robotic Automation Systems', (Electric Power Research Institute (EPRI), Inc., 2002)
[27] Vegunta, S.C. and Milanović, J.V.: 'Investigation of Voltage Disturbances in a Typical Pharmaceutical Customer Facility', Power Systems Computation Conference (PSCC), (Curran, 2008), pp. 1-7
[28] Targosz, R. and Manson, J.: 'Pan-European Power Quality Survey', International Conference on Electricity Distribution (CIRED), (2007), pp. 1-4
[29] Pearson, C.C. and Uthayanan, V.: 'The BSRIA Power Quality Guide', (BSRIA Ltd., 2000, AG 2/2000 doc. no.)
[30] Boemer, J.C.*, et al.*, 'Status of revision of IEEE Std 1547 and 1547.1', in, IEEE Power & Energy Society General Meeting, (2017), pp. 1-5
[31] 'Digest of United Kingdom Energy Statistics (DUKES) 2016', (Department for Business, Energy & Industrial Strategy, UK Government, 2016)
[32] 'Changes to the Distribution Code and Engineering Recommendation G59: Frequency Changes during Large Disturbances and their Impact on the Total System (Authority Decision - Distribution Code and ER G59)', (Ofgem, UK Government, 2014), pp. 1-1
[33] 'GC0079 Frequency Changes during Large Disturbances and their Impact on the Total System - Stage 03: Industry Consultation', (National Grid Electricity Transmission plc, 2017), pp. 5-5
[34] Djokic, S.*, et al.*: 'On Evaluation of Power Electronic Devices' Efficiency for Nonsinusoidal Voltage Supply and Different Operating Powers', IEEE Transactions on Instrumentation and Measurement, 2017, 66, (9), pp. 2216-2224
[35] IEC/TR 61000-3-15:2011: 'Electromagnetic compatibility (EMC) - Part 3-15: Limits - Assessment of Low Frequency Electromagnetic Immunity and Emission Requirements for Dispersed Generation Systems in LV Network', 2011
[36] 'Enhanced Frequency Response', https://www.nationalgrideso.com/balancing-services/frequency-response-services/enhanced-frequency-response-efr, accessed 17th Jan. 2017
[37] 'Enhanced Frequency Response - Invitation to Tender for Pre-qualified Parties', (National Grid Electricity Transmission plc, 2016)
[38] 'Distributed Generation EHV Constraint Maps', https://www.westernpower.co.uk/Connections/Generation/Distributed-generation-EHV-constraint-maps.aspx, accessed 20th July 2017
[39] Vegunta, S.C., Twomey, P., and Randles, D.: 'Impact of PV and Load Penetration on LV Network Voltages and Unbalance and Potential Solutions', International Conference and Exhibition on Electricity Distribution (CIRED), (2013), pp. 1-4
[40] 'Distributed Generation: Flexible Distributed Generation (FDG) Connections', https://www.ukpowernetworks.co.uk/internet/en/our-services/list-of-services/electricity-generation/flexible-distributed-generation/, accessed 20th July 2017
[41] 'IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces', IEEE Std 1547-2018 (Revision of IEEE Std 1547-2003), 2018, pp. 1-138
[42] Bletterie, B., Bründlinger, R., and Fechner, H.: 'Sensitivity of Photovoltaic Inverters to Voltage Sags - Test Results for a Set of Commercial Products', International Conference and Exhibition on Electricity Distribution (CIRED), (2005), pp. 1-4
[43] ENA EREC G59/3-4: 'Recommendations for the Connection of Generating Plant to the Distribution Systems of Licensed Distribution Network Operators', 2018
[44] ENA EREC G83/2: 'Recommendations for the Connection of Type Tested Small-scale Embedded Generators (Up to 16A per Phase) in Parallel with Low-Voltage Distribution Systems', 2012
[45] Probert, S. and Nutt, S.: 'Generator Fault Ride Through (FRT) Investigation: Stage 1 Literature Review', (Transpower New Zealand Limited, 2009)
[46] 'Infographic: The energy network', (OFGEM, UK Government, 2017)
[47] 'Power Quality', https://www.ema.gov.sg/Power_Quality.aspx, accessed 20th July 2017
[48] 'Statistics: SAIDI & SAIFI', https://www.ema.gov.sg/statistic.aspx?sta_sid=20140730ZvSQHDO0JvBm, accessed 20th July 2017
[49] 'Statistics: Voltage Dip Incidents', https://www.ema.gov.sg/statistic.aspx?sta_sid=20140730d62kE8xTUBib, accessed 20th July 2017
[50] 'Electricity Distribution Company Performance 2010 to 2015', (OFGEM, UK Government, 2015)
[51] 'RIIO-ED1 Annual Report 2016-17', (OFGEM, UK Government, 2017), pp. 36-37
[52] Larsen, P.H.*, et al.*: 'Assessing Changes in the Reliability of the U.S. Electric Power System', (Lawrence Berkeley National Laboratory, 2015)
[53] 'Electricity Distribution Annual Report for 2010-11', (OFGEM, UK Government, 2012, 46/12 doc. no.)
[54] Schwab, K.: 'The Global Competitiveness Report 2017-2018', (World Economic Forum, 2017), pp. 35-51
[55] 'Application of Overhead Line Switchgear and Protection Systems', (SP Power Systems Limited, 2012, ESDD-02-011 doc. no., 7 edn.), pp. 3-4
[56] '2008/09 Electricity Distribution Quality of Service Report', (OFGEM, UK Government, 2009, 162/09 doc. no.)

[57] 'Electricity Distribution Price Control Review Final Proposals - Allowed Revenue Cost Assessment', (OFGEM, UK Government, 2009)
[58] BS EN 50160:2010+A1:2015: 'Voltage Characteristics of Electricity Supplied by Public Electricity Networks', 2015
[59] 'CEER Benchmarking Report on The Quality of Electricity and Gas Supply, Chapter 3: Electricity – Voltage Quality', (Council of European Energy Regulators (CEER), 2016, C16-EQS-72-03 doc. no., 6th edn.)
[60] 'Smart Metering Implementation Programme - Progress Report for 2018', (DECC, UK Government, 2018)
[61] 'Smart Metering Implementation Programme - Government Respons e to the Consultation on the Second Version of the Smart Metering Equipment Technical Specifications Part 1', (DECC, UK Government, 2013)
[62] 'Smart Metering Implementation Programme - Smart Metering Equipment Technical Specifications Version 2', (DECC, UK Government, 2013)
[63] IEC/TR 61000-3-7: 2008, ed. 2: 'Assessment of Emission Limits for the Connection of Fluctuating Installations to MV, HV and EHV Power Systems', 2008
[64] SEMI F47-0706 'Specification for Semiconductor Processing Equipment Voltage Sag Immunity', 2012
[65] Cebrian, J.C., Kagan, N., and Milanović, J.V.: 'Probabilistic Estimation of Distribution Network Performance With Respect to Voltage Sags and Interruptions Considering Network Protection Setting—Part I: The Methodology', IEEE Transactions on Power Delivery, 2018, 33, (1), pp. 42-51
[66] Cebrian, J.C., Kagan, N., and Milanović, J.V.: 'Probabilistic Estimation of Distribution Network Performance With Respect to Voltage Sags and Interruptions Considering Network Protection Setting—Part II: Economic Assessment', IEEE Transactions on Power Delivery, 2018, 33, (1), pp. 52-61
[67] ENA EREC G5/5 (Draft): 'Planning Levels for Harmonic Voltage Distortion and the Connection of Non-Linear Equipment to Transmission Systems and Distribution Networks in the United Kingdom', 2015
[68] ENA EREC G5/4-1, iss. 1: 'Planning Levels for Harmonic Voltage Distortion and the Connection of Non-Linear Equipment to Transmission Systems and Distribution Networks in the United Kingdom', 2005
[69] Thallam, R.S. and Heydt, G.T., 'Power Acceptability and Voltage Sag Indices in the Three Phase Sense', in, 2000 Power Engineering Society Summer Meeting (Cat. No.00CH37134), (2000), pp. 905-910 vol. 902
[70] IEC TR 61000-2-8, ed 1.0: 'Electromagnetic compatibility (EMC) - Part 2-8: Environment - Voltage Dips and Short Interruptions on Public Electric Power Supply Systems with Statistical Measurement Results', 2002
[71] 'IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems', IEEE Std 493-2007 (Revision of IEEE Std 493-1997) - Redline, 2007, pp. 1-426
[72] 'Sub-national Electricity and Gas Consumption Summary Report 2015', (Department for Business, Energy, & Industrial Strategy, UK Government, 2016)
[73] 'Distribution Charges Overview', http://www.energynetworks.org/electricity/regulation/distribution-charging/distribution-charges-overview.html, accessed 20th July 2017
[74] Druce, R., *et al.*: 'Engineering Recommendation P2 Review Workstream 2.7: Alignment of Security of Supply Standard in Distribution Networks with Other Codes and Schemes', (NERA Economic Consulting, 2015)
[75] 'Strategy Decision for the RIIO-ED1 Electricity Distribution Price Control - Outputs, Incentives and Innovation', (OFGEM, UK Government, 2013, 26a/13 doc. no.), pp. 22-80
[76] Chan, J.Y.: 'Framework for Assessment of Economic Feasibility of Voltage Sag Mitigation Solutions', Ph.D. Thesis, The University of Manchester, 2010
[77] Bollen, M.H.J., *et al.*, 'Voltage Dip Immunity of Equipment and Installations - Message to Stakeholders', in, IEEE 15th International Conference on Harmonics and Quality of Power, (2012), pp. 915-919